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Metamaterials and Metasurfaces in THz Applications

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Abstract: We present a set of terahertz optical components, such as linear and circular polarizers, absorbers, devices with enhanced transmittance, and single layer chiral systems based on metamaterials. Discussion covers design rules, fabrication and characterization.

1. Introduction

Metamaterials (MMs) as a design concept have demonstrated a broad range of useful properties in different ranges of frequencies. The main advantage of the metamaterial-based devices is the possibility to broaden both passive and active photonic component functionalities. While in the visible, near infrared or microwave regimes these issues in principle have strong alternatives via a conventional optics approach, at terahertz (THz) frequencies MMs are often considered as being the unique solution for the encountered problems, see e.g. reviews [1,2]. Several approaches involving MMs-based passive THz components have been proposed and show good potential for applications [3-5]. Here we present our efforts in exploiting the metamaterials properties in this frequency range.

2. Design

In design we address the question of effective control of the THz waves polarization state: for example, polarization conversion using chiral metasurfaces and improved transmission through metallic grids with the help of an antireflection coating.

For unified approach in the MMs design we employ the transmission line theory providing a needed level of the generalization. We demonstrate its applicability in optical problems by analyzing the theoretical limits of a metamaterial-based converter with orthogonal linear eigenpolarizations that allows for linear-to-elliptical polarization transformation with any desired ellipticity and ellipse orientation. Our analysis reveals that the maximal conversion efficiency with a single metamaterial surface is 50 % in transmission and up to 90% in reflection. However, a double layer transmission converter and a single layer with a metallic mirror can have 100% polarization conversion efficiency. We tested our conclusions numerically reaching the designated limits of efficiency using a simple metamaterial design and checking them against the numbers reported in literature. Our general analysis provides useful guidelines for the metamaterial design.

3. Fabrication and characterization

We utilize mostly two fabrication procedures for THz MMs, both of them based on photolithography. The first fabrication process (see one cycle of the process flow in Fig.1(a)) is aimed at obtaining multi-level metamaterials [6]. In this case, several aligned exposures increase the complexity of the fabrication process.

The second one (Fig 1(b)) is a newly developed process for fabricating high aspect ratio, free-standing metal films suspended in air. On demand, e.g. due to the extended THz beam spot size, the membranes can be fabricated with an area 8x8 mm^2. Such membranes, due to their simplicity and flexibility, are a great test platform for designs that are sensitive to substrates.

The two approaches may be combined rendering a complex multilayer membrane structure. The first results from this combined process flow will be presented during the conference.

We use terahertz time-domain spectroscopy (THz-TDS), which employs the air plasma generation of ultrashort THz transients in combination with air biased coherent detection of the THz transients [7]. Both the generation and detection processes are based on the four-wave mixing in air. With air as the nonlinear medium the phase matching conditions are satisfied over an extremely broad bandwidth range, and therefore the bandwidth of the generation and detection processes is in practice limited only by the laser bandwidth. We use a transform-limited 35-fs laser pulse, resulting in THz transients with a spectral coverage from 1 to 20 THz and THz pulse duration of less than 50 fs. In combination with a standard THz-TDS system based on photoconductive switches covering the low THz range we can perform quantitative reliable THz-TDS in the 0.05-20 THz range [8].

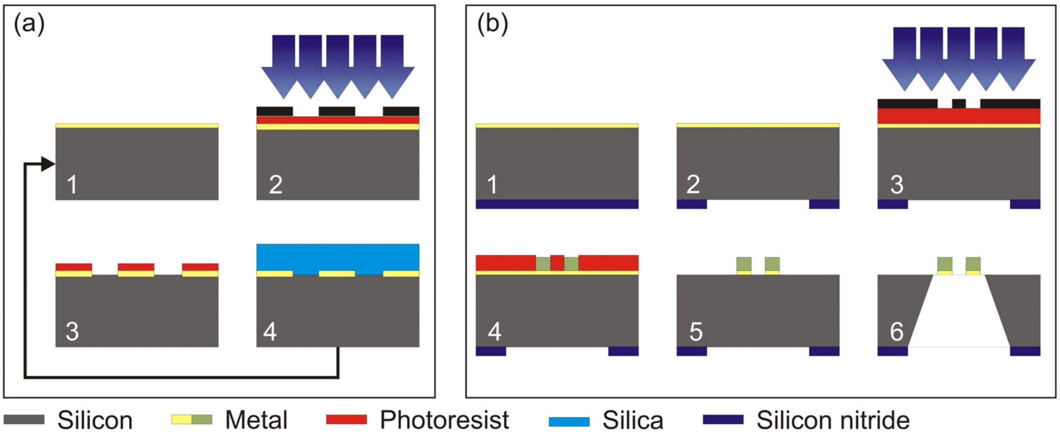

Fig.1 Two examples of fabrication flows. (a) Fabrication of multilayer structures using a step-and-repeat process where at each step a new patterned metallic layer is added aligned with the ones previously deposited. (b) Membrane fabrication process where the structure is grown electrochemically. The substrate is removed and thus a free-standing metallic membrane with desired functionality (not to scale) is obtained.

4. Discussions and conclusions

One example of application, where the multilayer process is used, is a transparent electrode design in the THz domain. The measured transmittance of the electrode itself (in fact, a metallic grid) is around 20%. By adding an extra metallic layer we employed the scattering cancellation mechanism to improve the total transmittance up to 95% [6].

Process flow for membrane fabrications was utilized to achieve metamaterial with strong optical activity and circular polarization conversion. Free-standing membranes MMs are exemplified by a dimer system, consisting of air slits patterned in a uniform 2μm-thick Ni film. Depending on arrangement of both slits and their sizes different optical properties of such metasurface (or plane MM) can be acquired. We demonstrate linear polarization filtering with the parallel slits dimmers, and more complex chiral behaviour of dimers, when non-equal slits are non-parallel. In particular, strong optical activity and circular polarization conversion are observed.

We also speculate on the concept of THz-optical modulator, where instead of broadly accepted semiconductors [2] a nonlinear dielectric material is incorporated [9]. As for a real device modeling we employ one of the chalcogenide glasses whose nonlinear constants are assumed as in the optical domain. The level of the control THz field is greatly mitigated by using a nanoslit in a metal coating. In this case, the non-resonance enhancement of the THz field reaches 100 times. By such arrangement the level of $\pi/2$ phase-shifting THz field is estimated to be near 20 kV/cm, which is feasible in current THz generating setups.

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